

# Magnetic flux stabilizing thin accretion disks

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## ABSTRACT

We calculate the minimal amount of large-scale poloidal magnetic field that has to thread the inner, radiation-over-gas pressure dominated region of a thin disk for its thermal stability. Such a net field amplifies the magnetization of the saturated turbulent state and makes it locally stable. For a  $10M_{\odot}$  black hole the minimal magnetic flux is  $10^{24}(\dot{M}/\dot{M}_{\text{Edd}})^{20/21} \text{ G} \cdot \text{cm}^2$ . This amount is compared with the amount of uniform magnetic flux that can be provided by the companion star – estimated to be in the range  $10^{22} - 10^{24} \text{ G} \cdot \text{cm}^2$ . If accretion rate is large enough, the companion is not able to provide the required amount and such a system, if still sub-Eddington, must be thermally unstable. The peculiar variability of GRS 1915+105, an X-ray binary with the exceptionally high BH mass and near-Eddington luminosity, may result from the shortage of large scale poloidal field of uniform polarity.

**Key words:** accretion, accretion discs – black hole physics

## 1 INTRODUCTION

According to the standard model, radiatively efficient, radiation pressure supported accretion disks are thermally and viscously unstable (Lightman & Eardley 1974; Shakura & Sunyaev 1976; Piran 1978). This prediction is in apparent disagreement with the properties of most black hole (BH) X-ray binaries. Except for two sources (GRS1915+105 and IGR J17091-3624, see Belloni et al. (2000) and Altamirano et al. (2011)), all other BH transients stay in their thermal, high/soft states for days/months without any sign of unstable behavior. The question arises – what phenomena does the standard model not account for?

One possibility for explaining the stability of radiation pressure dominated thin disks is the presence of a strong magnetic field which provides additional pressure support and prevents the runaway heating or cooling that would occur without it. This idea has been investigated in recent years by Oda et al. (2009) and Zheng et al. (2011), and very recently verified numerically by Sądowski (2016). Recently, Li & Begelman (2014) have shown that magnetic fields may help stabilize the disk also through magnetically driven outflows which decrease the disk temperature and thus help the disk become more stable at a given accretion rate. The stabilizing effect of strong fields on disk thermal instability was also discussed by Begelman & Pringle (2007).

How to make an accretion disk magnetized enough to prevent thermal runaway? Magnetorotational instability (MRI, Balbus & Hawley 1991) in an isolated box is known to saturate at a total to magnetic pressure ratio  $\beta = p_{\text{tot}}/p_{\text{mag}} \approx 10$  (e.g., Turner 2004; Hirose et al. 2009). However, if large scale magnetic field threads the box, either vertically or radially, the saturated magnetic field is

much stronger. In particular, Bai & Stone (2013) have shown that the presence of a weak net vertical magnetic field characterized by  $\beta_0 = 1000$  already leads to a saturated state where magnetic field contributes to roughly half of the total pressure, which is the rough threshold for the thermal stability (Sądowski 2016). Consistent results have recently been obtained by Salvesen et al. (2016).

In this paper we investigate how much magnetic flux contained in large scale vertical field is needed to stabilize a geometrically thin, radiatively efficient accretion flows with radiation pressure dominating over thermal pressure. We compare this quantity with rough estimates of the magnetic flux that can be provided by the companion stars, and with the amount of flux required for the magnetically arrested (MAD) state.

Our work is organized as follows. In Section 2 we calculate the magnetic flux required for disk stabilization. The flux required for the magnetically arrested state is calculated for comparison in Section 3. In Section 4 we estimate how much uniform magnetic field a companion star can provide. The discussion is given in Section 5 and our work is summarized in Section 6.

## 2 MAGNETIC FLUX REQUIRED FOR DISK STABILIZATION

In this Section we estimate the minimal amount of poloidal vertical flux required for thermal stability of an accretion disk. We assume that the disk is locally stable if at least 50% of the pressure is provided by the magnetic field (Sądowski 2016). Such a highly magnetized state is obtained when disk is threaded by net vertical magnetic field satisfying  $\beta_0 \lesssim 1000$ , i.e., the pressure of the large scale component equals to at least one part in thousand of the sum of radiation and thermal pressures in the equatorial plane

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(Bai & Stone 2013; Salvesen et al. 2016). The minimal amount of magnetic flux required for stability of the entire disk is obtained by integrating the net vertical flux over the whole otherwise unstable region, i.e., where radiation pressure exceeds gas pressure. Doing so we also assume that no magnetic flux has accumulated at the BH.

In the standard  $\alpha$ -disk model (Shakura & Sunyaev 1973) the vertically integrated total pressure  $P$  at radius  $R$  is determined solely by the angular momentum conservation,

$$2\pi R^2 \alpha P_{\text{tot}} = \dot{M} \left( \sqrt{GM_{\text{BH}} R} - \sqrt{GM_{\text{BH}} R_{\text{in}}} \right), \quad (1)$$

where  $\dot{M}$  is the accretion rate,  $M_{\text{BH}}$  is the mass of the BH,  $G$  is the gravitational constant,  $\alpha$  is the disk viscosity parameter, and  $R_{\text{in}} = 6R_{\text{G}} = 6GM/c^2$  is the location of the inner edge of the disk<sup>1</sup>. In cgs units it equals,

$$P_{\text{tot}} = 8 \times 10^{23} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right) \left( \frac{R}{R_{\text{G}}} \right)^{-3/2} \left( \frac{\alpha}{0.1} \right)^{-1} \text{ J erg/cm}^2, \quad (2)$$

where  $\dot{M}_{\text{Edd}} = 2.48 \times 10^{18} M_{\text{BH}}/M_{\odot} \text{ g/s}$  is the Eddington accretion rate (which, according to this definition, corresponds to a thin disk emitting the Eddington luminosity), and  $J = 1 - \sqrt{R_{\text{in}}/R}$ .

The strength of the net vertical field that is required to provide highly magnetized saturated turbulent state is given with respect to the equatorial plane pressure, not the vertically integrated one. This may be estimated knowing the disk half-thickness  $H$  which for the radiation pressure dominated regime of the standard thin disk solution equals (Shapiro & Teukolsky 1983),

$$H = 2 \times 10^7 \left( \frac{M_{\text{BH}}}{10M_{\odot}} \right) \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right) \text{ J cm}. \quad (3)$$

The equatorial plane total pressure  $p_{\text{tot}}$  now equals  $p_{\text{tot}} = P_{\text{tot}}/2H$ .

According to our assumptions, half of the total pressure comes from the magnetic field. The remaining amount is the sum of the radiation and thermal pressure. The strength of the net vertical field,  $B_0^z$ , that was needed to enhance the magnetization of the saturated state, is,

$$\begin{aligned} B_0^z &= \sqrt{8\pi \frac{p_{\text{tot}}}{2\beta_0}} = \\ &= 2 \times 10^7 \left( \frac{M_{\text{BH}}}{10M_{\odot}} \right)^{-1/2} \left( \frac{R}{R_{\text{G}}} \right)^{-3/4} \left( \frac{\beta_0}{1000} \right)^{-1/2} \left( \frac{\alpha}{0.1} \right)^{-1/2} \text{ G}. \end{aligned} \quad (4)$$

The total required flux is obtained by integrating  $B_0^z$  over otherwise unstable region. The radiation pressure dominates over gas pressure in the inner region up to a critical radius  $R_{\text{max}}$  (Shapiro & Teukolsky 1983),

$$R_{\text{max}}/R_{\text{G}} = 9 \times 10^2 \left( \frac{M_{\text{BH}}}{10M_{\odot}} \right)^{2/21} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{16/21} \left( \frac{\alpha}{0.1} \right)^{2/21}. \quad (5)$$

Performing the integral one obtains<sup>2</sup>

$$\Phi_0 = 1 \times 10^{24} \left( \frac{M_{\text{BH}}}{10M_{\odot}} \right)^{34/21} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{20/21} \left( \frac{\beta_0}{1000} \right)^{-1/2} \left( \frac{\alpha}{0.1} \right)^{-8/21} \text{ G-cm}^2. \quad (6)$$

When calculating the minimal amount of large scale magnetic flux required for stabilization of the disk we have implicitly assumed that the accretion flow, which at the accretion rates of interest is geometrically thin, was able to advect this net magnetic field inward into the inner region. Whether or not the large-scale

field can be advected depends on the balance between the advection and diffusion of the field. Standard geometrically thin disks drag vertical magnetic field inefficiently (Lubow et al. 1994; Ghosh & Abramowicz 1997), and therefore are unlikely to drag significant amount of magnetic field on to the BH. If magnetic field accumulates there it exerts significant outward pressure on the accretion flow (see the discussion of the magnetically arrested state in Section 3). The net magnetic field that we require for stabilization does not need to accumulate on the BH – it is enough if it threads the disk itself and its pressure is a factor  $\beta_0$  lower than the total pressure. The radial gradient of such net-field pressure is negligible in thin accretion disks when compared with gravitational and centrifugal forces. In other words, it is only the magnetic tension that has to be overcome, not the radial gradient of pressure (as in the MAD state). Whether or not sub-Eddington disk are able to drag even such a small amount of field inward, is still debated (see e.g., Guilet & Ogilvie 2012, 2013; Avara et al. 2015). Our work bases on the assumption that it is possible.

## 2.1 Application to BH binaries

Equation 6 gives the minimal amount of magnetic flux of uniform polarity that has to be provided to thermally stabilize radiatively efficient, radiation-over-gas pressure dominated thin disks. This amount depends on the BH mass ( $M_{\text{BH}}$ ) and the accretion rate ( $\dot{M}$ ), as well as two other parameters ( $\beta_0$  and  $\alpha$ ) that result from non-linear evolution of MRI and are likely to have rather weak or no dependence at all on the former two. Therefore, the amount of required magnetic flux scales mostly with the BH mass and the accretion rate.

There are ~20 low-mass X-ray binaries with existing dynamical estimates of the compact object mass indicating towards BHs (e.g., Özel et al. 2010). The masses of the transient objects range from ~5 to ~12  $M_{\odot}$ . Most such systems undergo transitions from the quiescent states to outbursts when they reach significant fractions of the Eddington luminosity (Dunn et al. 2010) and enter the radiation-over-gas pressure dominated, presumably unstable, regime.

To estimate how much magnetic flux of uniform polarity is required for stabilization of each source one needs some measure of the accretion rate. For this purpose we take the luminosity at outburst maximum as given in Table 2 of Steiner et al. (2013)<sup>3</sup>. In Table 1 we show the masses, accretion rate estimates and the required fluxes (Eq. 6, obtained assuming the fiducial values of  $\beta_0$  and  $\alpha$ ) for the five BH X-ray binaries with well established BH masses and existing estimates for the peak luminosities (compiled from Steiner et al. (2013) and Fragos & McClintock (2015)). The amount of magnetic flux required for their stabilization ranges from  $6.8 \times 10^{22}$  to  $5.7 \times 10^{23} \text{ G-cm}^2$ . The source that requires by far most of uniform large scale magnetic flux (almost three times more than the second one) is GRS 1915+105. This particularly high number results from the largest BH mass and accretion rate which determine the physical size of the radiation-over-gas dominated region that has to be stabilized by providing external large scale net vertical field. GRS 1915+105 is at the same time the only source with well established parameters that shows long duration, very rapid and short timescale variability near the Eddington luminosity (e.g., Belloni et

<sup>1</sup> In this work we ignore, for simplicity, the BH rotation.

<sup>2</sup>  $1 \text{ G-cm}^2 = 1 \text{ Maxwell (Mx)}$ .

<sup>3</sup> Because the thin disk geometry may not apply to magnetic pressure dominated disks, we adopt their  $L_{\text{Peak}}$  that was obtained assuming isotropic emission.

**Table 1.** Magnetic fluxes required to stabilize particular BH X-ray binaries

Name	$M_{\text{BH}}/M_{\odot}$	$L_{\text{Peak}}/L_{\text{Edd}}$	$\Phi_0 [\text{G} \cdot \text{cm}^2]$
GRS 1915+105	12.4	1.0	$5.7 \times 10^{23}$
XTE J1550-564	9.1	0.53	$1.9 \times 10^{23}$
GRS 1124-683	7.0	0.61	$1.4 \times 10^{23}$
A0620-00	6.6	0.47	$1.0 \times 10^{23}$
GRO J1655-40	6.3	0.34	$6.8 \times 10^{22}$

Masses and luminosities compiled from [Steiner et al. \(2013\)](#), [Reid et al. \(2014\)](#) and [Fragos & McClintock \(2015\)](#).

al. 2000) that results, presumably, from thermal instability of its accretion disk. One should note, however, that the exceptionally high mass and luminosity of GRS 1915+105 are not the only properties making it stand out. At the same time it has the longest orbital period, the largest accretion disk, a giant companion star ([Greiner et al. 2001](#)) and presumably also the largest BH spin ([McClintock et al. 2006](#)).

### 3 MAGNETIC FLUX REQUIRED FOR THE MAGNETICALLY ARRESTED STATE

Magnetic flux that is advected across the inner edge of the disk accumulates on the BH. If advection is efficient the accumulated magnetic field exerts radial pressure large enough to dynamically affect the infalling gas. When this outward magnetic pressure roughly balances the radial gravitational force, the disk enters the magnetically arrested state (MAD), where accretion is possible only because the interchange instability allows the gas to penetrate the accumulated field by breaking into clumps or filaments ([Narayan et al. 2003](#); [Tchekhovskoy et al. 2011](#)).

The amount of magnetic flux accumulated at the BH which results in the MAD state extending up to a given radius was estimated by [Narayan et al. \(2003\)](#) (their Eq. 2). Taking the horizon radius as the limit of the extent of the MAD regime, one obtains the minimal amount of flux required to provide the saturated magnetic field at the BH (see also [Yuan & Narayan 2014](#)),

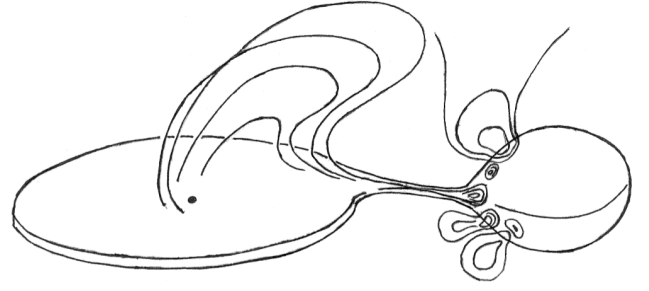
$$\Phi_{\text{MAD}} = 1 \times 10^{23} \left( \frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{3/2} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{1/2} \left( \frac{\epsilon}{10^{-2}} \right)^{-1/2} \text{G} \cdot \text{cm}^2, \quad (7)$$

where  $\epsilon$  is the ratio of the gas radial velocity to the free-fall velocity. If only such an amount is advected on the BH, the innermost part of the flow will be in the MAD state, and the BH itself, if rotating, will efficiently generate relativistic magnetic jets ([Blandford & Znajek 1977](#)).

### 4 MAGNETIC FLUX PROVIDED BY THE COMPANION STAR

The companion stars in most BH X-ray binaries overflow their Roche lobes and transfer gas to the compact object. The expelled matter forms an accretion disk and gradually approaches the black hole, sometimes in a rather violent way due to the ionization instability modulating the flow ([Lasota 2001](#)). The gas drawn from the stellar surface brings magnetic field with it which triggers turbulence in the accretion disk. One may expect, that such magnetic field will have some coherence which will determine the amount of poloidal magnetic flux of uniform polarity available in the accretion disk. Below we very roughly estimate that amount.

It is reasonable to expect that the companion stars in low mass



**Figure 1.** Schematic picture of the advection of magnetic tubes from the surface layers of the companion star towards the inner region of the accretion disk in an X-ray binary.

X-ray binaries are tidally locked to the rotation of the binary system. This fact has significant consequences. Firstly, the gas that overflows the Roche lobe comes from exactly the same substellar spot on the companion star surface. Therefore, the magnetic field advected with the gas towards the compact object will simply reflect the magnetic field in the surface layers of the star, and will not be affected by sweeping through the stellar surface due to rotation. Secondly, tidal locking modifies the rotational period of the companion star, which is one of the major factors determining the efficiency of magnetic field generation in the stellar interior.

For obvious reasons the magnetic field of the Sun is known best (see e.g., [Schrijver & Zwaan 2000](#)). It exhibits 11 year long activity cycles over which the polarity of the dipolar component flips. Over that period Solar activity changes as well. During the activity periods multiple flares, coronal mass ejections, and sunspots occur on the surface. These phenomena are related to the emergence of magnetic field, either in the form of large closed loops or open field lines, which is generated within the convective envelope of the Sun through the dynamo process ([Parker 1955](#)). Emerging magnetic field probes the magnetic field properties below the stellar surface. In particular, one may expect that the magnetic field below the surface forms magnetic field loops containing similar magnetic flux as the loops penetrating the stellar surface. The magnetic tubes in the surface layers will be advected with the gas and may dominate the large-scale properties of the magnetic field in the accretion disk (Fig. 1).

The magnetic field near the active regions in the Sun can reach and exceed  $\sim 2000 \text{ G}$  ([Aschwanden 2004](#)). The sizes of Solar sunspots hardly exceed 0.001 of the solar hemisphere area ([Harvey & Zwaan 1993](#)). Multiplying these two numbers (magnetic field strength by the estimate of its coherence area) one gets the estimate of the maximal amount of magnetic flux in an active region (reflecting roughly the amount of magnetic flux in coherent regions below the surface) –  $\Phi_{\odot} \lesssim 10^{23} \text{ G} \cdot \text{cm}^2$ . [Linsky & Schöller \(2015\)](#) give the range of magnetic fluxes in individual active regions on the Sun as  $10^{20}$  to  $10^{22.5} \text{ G} \cdot \text{cm}^2$ , roughly consistent with the previous estimate.

Direct measurements of magnetic flux contained in single magnetic tubes in distant stars is in most cases impossible. Magnetic fields on stars are implied from the spatially-unresolved stellar light of nearby stars which provides information only about the integrated (affected by cancellations of magnetic field of opposing polarity) magnetic field. Even Zeeman Doppler imaging (e.g., [Donati & Landstreet 2009](#)) can measure only the net (again affected by cancellations) magnetic field in active regions.

Companion stars in X-ray binaries differ from the Sun in many aspects (for rather comprehensive list BH X-ray binaries properties

see [Fragos & McClintock 2015](#)). They show different masses and spectral types. Most are K or M type dwarfs with masses between  $0.2$  and  $0.9M_{\odot}$ . Some (e.g., the companion of GRS 1915+105) are evolved giants. Still, all of them have one common property – rapid rotation resulting from tidal synchronization of the companion star with the binary. Almost half of the systems with well established parameters of both BH and the companion star have orbital (and rotational) periods below  $0.5$  d (the Sun rotates at the equator with  $\sim 24$  d period). Only one BH X-ray binary rotates with a longer period than the Sun (GRS 1915+105,  $\sim 34$  d), but this rate of rotation is still exceptional for a giant star. It is unclear to what level and for how long the tidally synchronized companions retain differential rotation of their interiors.

Like in the Sun, the stellar magnetic fields are assumed to result from the dynamo activity in their differentially rotating convective zones. This assumption is supported by observations showing that the activity indeed scales with rotation, in agreement with the dynamo theory ([Reiners 2012](#)). This relation can be characterized by the Rossby number,  $R_0$  – the ratio of the rotational period of the star and its convective turnover time (e.g., [Stepien 1994](#)). [Reiners et al. \(2009\)](#) have shown that the magnitude of the mean surface magnetic field of K and M dwarfs saturates around  $3000$  G for  $R_0 < 10^{-1.5}$ , and scales like  $1/R_0$  for larger values. The stars with saturated magnetic fields strength are the fastest rotators (orbital periods  $\lesssim$  days) – quite similar to most of the BH X-ray binary companions. The Rossby number of the Sun is of the order of unity ([Reiners 2012](#)). Therefore, if the Sun was rapidly rotating and Sun-like stars followed the same dependence on the Rossby number, its mean magnetic field would be 10 to 100 times stronger than it is presently. If the size of the active regions stayed the same (a conservative assumption), the magnetic flux contained in a single magnetic tube would increase by a similar factor.

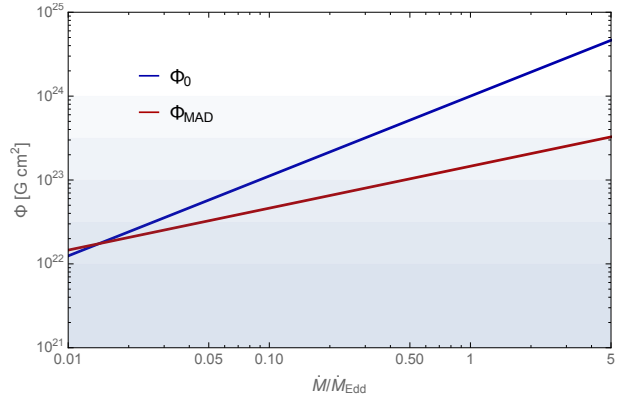
We conclude that the amount of the magnetic flux of uniform polarity that the companion star provides depends strongly on the star properties, most importantly its rotation, but also mass and evolutionary history. A rapidly rotating Sun would likely provide at most  $10^{22} - 10^{24} \text{ G} \cdot \text{cm}^2$ . It is not possible to give a comparable estimate for any of the companion stars in X-ray binaries due to our lack of understanding of magnetic properties of distant stars, especially ones tidally locked and significantly affected by evolution. We therefore take the range specific for the fast rotating Sun only as the ballpark for what the companion stars can provide.

## 5 DISCUSSION

In the previous sections we estimated magnetic fluxes required for the thermal stability of a thin accretion disk, for the MAD state, and provided by the companion stars. All three of them turn out to have the same order of magnitude for near-Eddington accretion rates and stellar mass BHs. It is somewhat surprising, especially when comparing the first two with the magnetic flux provided by the stellar companion which is determined by the efficiency of stellar dynamo which knows nothing about the properties of the inner regions of accretion disks.

Figure 2 shows how the fluxes required for stabilization and for the magnetically arrested state change with accretion rate for the fiducial parameters ( $M_{\text{BH}} = 10M_{\odot}$ ,  $\beta_0 = 1000$ ,  $\alpha = 0.1$ , and  $\epsilon = 0.01$ ). Both increase with the accretion rate, but the flux required for stabilization ( $\Phi_0$ , blue line) grows faster. At roughly  $0.01\dot{M}_{\text{Edd}}$  they have the same value,  $\sim 10^{22} \text{ G} \cdot \text{cm}^2$ .

The shaded region in the background reflects the rough esti-



**Figure 2.** Minimal magnetic flux required for stabilization of a thin disk ( $\Phi_0$ , blue line), as a function of normalized accretion rate. Red line denotes the minimal amount of magnetic flux required for the magnetically arrested (MAD) state ( $\Phi_{\text{MAD}}$ ). These fluxes were calculated assuming  $M_{\text{BH}} = 10M_{\odot}$ ,  $\beta_0 = 1000$ ,  $\alpha = 0.1$ , and  $\epsilon = 0.01$ . The shaded region reflects the rough estimate of the maximal magnetic flux provided by the companion star ( $10^{22} - 10^{24} \text{ G} \cdot \text{cm}^2$ , Section 4).

mate of the amount of the uniform magnetic flux that can be provided by the companion star,  $10^{22} - 10^{24} \text{ G} \cdot \text{cm}^2$  (Section 4). It is clear that for a fixed value of that quantity, i.e., for a given companion star, there is a critical accretion rate above which the flux provided by the companion is not enough to stabilize the unstable inner region of the accretion flow. Therefore, each X-ray binary system becomes unstable if this critical accretion rate (specific for each system) is exceeded. One may expect that this critical value is of the order of the Eddington accretion rate.

If the companion star is capable of providing plenty of magnetic field of uniform polarity, then such a critical accretion rate would exceed the Eddington one and a given system will never become unstable since super-Eddington accretion flows are stabilized by advection of heat (see [Abramowicz et al. 1988](#)).

Qualitatively similar conclusion applies to the amount of flux required for the magnetically arrested disk – even if the advection of magnetic field allows for the field accumulation on the BH, there exists a critical, near-Eddington accretion rate above which the MAD state cannot be sustained. In other words, highly super-Eddington accretion flows cannot be magnetically arrested and efficiently produce magnetically-driven, relativistic jets (although they are likely to generate radiative jets, see [Sikora & Wilson 1981](#); [Narayan et al. 1983](#); [Sądowski & Narayan 2015](#)).

If only the companion star provides the large scale poloidal magnetic flux and this critical accretion rate for stabilization is indeed significant, then one would expect that X-ray binaries with most massive BHs and accreting at largest, but sub-Eddington, accretion rates will be most difficult to stabilize. Out of the best known BH X-ray binaries, GRS 1915+105 is such an example, with most massive BH and near-Eddington outburst luminosity, and it is indeed the only one unstable. It has to be mentioned, however, that its companion star is very evolved and presumably significantly affected by binary evolution ([Fragos & McClintock 2015](#)), and therefore peculiar within the set of other companion stars. Thus, the estimate of the magnetic flux available from the companion that we derived basing on Solar and dwarf star magnetic properties may not be accurate ([Stepien 1994](#)).

Thermal instability is not specific to BH accretion flows. Similar phenomenon is expected to take place in radiation pressure dominated, radiatively efficient disks around neutron stars (NSs). Simi-



larly to the BH case, large scale magnetic field may play important role in stabilizing them. In the case of NS systems, however, the magnetic field of the NS itself may provide extra stabilizing effect. In addition, low mass of NSs would suggest small amount of magnetic flux required for stabilization, relatively easier to provide by the companion star. Out of all NS systems known, only the Rapid Burster showed (twice in 16 years) light curves that resemble those of GRS 1915+105 (Bagnoli & in't Zand 2015) what seems to be consistent with the picture presented in this Letter.

Several questions, however, arise. We assumed that the magnetic flux is provided by the companion star, and the magnetic tubes reaching its surface layers near the substellar point are efficiently dragged into the inner region of the accretion disk. To provide the observed stability of outbursts of most X-ray binaries, the duration of which is determined by the propagation of viscous instability through the whole accretion disk and is often of the order of months (Lasota 2001), one would have to make sure that magnetic flux accumulated in the inner region is not canceled out by a flux of opposite polarity during this period. That would require either that a single magnetic tube is accreted for a longer time than the outburst duration, or that the net magnetic field of the tubes hover for such a time at fixed location in the disk having established the advection/diffusion equilibrium (analytical solutions of the steady-state radial distribution of poloidal fields were obtained and studied by Okuzumi et al. 2014). The latter may be preferred if thin accretion disks are indeed inefficient accretors of the magnetic field.

One other question is whether it is indeed the magnetic field from the active regions of the companion star that dominates the large scale magnetic structures in the disk. In principle, plasma-related effects may be operating as well. An example is the Contopoulos battery which can generate poloidal magnetic flux of uniform polarity as a result of the Poynting-Robertson radiative drag (Contopoulos et al. 2015). Although field generated in such a way is instantaneously insignificant, given enough time, it could aggregate to provide the amount of magnetic flux relevant in the context discussed in this work.

## 6 SUMMARY

We have calculated the minimal amount of large-scale poloidal magnetic flux that has to thread the inner part of a thin, radiation-over-gas pressure dominated accretion disk to stabilize it against thermal instability. We have compared that amount with the magnetic flux that has to accumulate on the BH to magnetically arrest the disk, and with the maximal magnetic flux of uniform polarity that can be advected with the gas from the companion star in X-ray binaries. We summarize our findings below, all of which depend on the assumptions that magnetic field can be advected inward and that the magnetic field coming from the companion star dominates the large-scale magnetic properties of the inner accretion disk region.

(i) *Magnetic flux required for stabilization:* – To stabilize the inner region of a thin accretion disk, where radiation pressure dominates over thermal pressure, one has to provide net poloidal flux of the order of  $10^{23} \text{ G} \cdot \text{cm}^2$  for  $\dot{M} = 0.1\dot{M}_{\text{Edd}}$  and  $10M_{\odot}$  BH (Eq. 6). Such a magnetic field, although weak when compared with the local gas and radiation pressures, will enhance the magnetization of the saturated state of MRI and lead to a magnetic pressure supported, and therefore stable, state. This critical amount of the large-scale magnetic flux grows with BH mass and the normalized accretion rate. This net magnetic field does not have to accumulate

on the BH and therefore can be relatively easily advected into the inner region.

(ii) *GRS 1915+105:* – Out of the BH X-ray binaries with well established BH and binary parameters, GRS 1915+105 requires most magnetic flux,  $\sim 6 \times 10^{23} \text{ G} \cdot \text{cm}^2$  to be stabilized due to its large BH mass and luminosity.

(iii) *Magnetic flux provided by the companion star* – In a tidally locked X-ray binary the gas accreting towards the compact object can drag magnetic field from the surface layers of the companion star. We estimated the amount of magnetic flux contained in magnetic tubes of rapidly rotating stars to be of the order of  $10^{22} - 10^{24} \text{ G} \cdot \text{cm}^2$ .

(iv) *Critical accretion rate for stabilization* – For a given system, the amount of magnetic flux required for stabilization above some critical, near-Eddington, accretion rate is larger than can be provided by the companion star. Such systems are expected to be thermally unstable (and GRS 1915+105 may be an example), unless their transfer rate exceeds the Eddington rate, in which case they are stabilized by the advection, and magnetic contribution is no longer required.

(v) *Magnetically Arrested Disk* – To saturate the magnetic flux accumulated at the BH, and to enter the MAD state resulting in efficient jet production, one has to provide a comparable amount of magnetic flux ( $\sim 10^{23} \text{ G} \cdot \text{cm}^2$  for  $1\dot{M}_{\text{Edd}}$ , Eq. 7). This state, however, requires significant accumulation of the magnetic field at the BH that exerts outward pressure and therefore requires very efficient advection of the magnetic field, which may not be the case for thin disks. Even if the advection is effective, when the accretion rate exceeds significantly the Eddington rate, the companion star cannot provide enough uniform magnetic flux to maintain the magnetically arrested state. Therefore, one should not expect efficient generation of relativistic jets in super-Eddington accretion flows.

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